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13. ABSTRACT (Maximum 200 words)

This research focuses on the problem of understanding the mechanisms by which the underwater spark is generated and the delivery of electrical energy to the arc load and ultimately the acoustic signal. Recent progress in numerical simulations of arc-generated bubbles in water show good agreement with experimental observations. The arc formation and dielectric breakdown of the water at moderate field strengths have been modeled with a fractal object. Good agreement with electrical characteristics has been obtained. The limitations of multi-gap electrodes in water have been characterized.

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Title: Plasma Sound Source Basic Research

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Description of Project

The plasma sound source (PSS) is an acoustic source used to generate high intensity low frequency sound. Applied Research Laboratories, The University of Texas at Austin (ARL:UT), is conducting a research and development program for the PSS that consists of both basic research and engineering development components. The basic research component provides the models and the fundamental physical understanding for the PSS, while the experiments and the large-scale hardware developed in the engineering effort provide a test bed of experimental data and equipment that allows the models to be tested for validity. The modeling capability and the experimental hardware that have been developed at ARL:UT have produced substantial improvements in plasma (spark) sound source technology. Previous research into the hydrodynamic properties of the PSS (ONR Grant 0018) provided acoustic models capable of predicting array signatures and acoustic characteristics of large numbers of interacting PSS elements. Furthermore, statistical thermodynamic models were developed to model the internal filling plasma, which gave insight into some aspects of the energy loss mechanisms associated with the PSS. These models provided little detailed understanding of the breakdown of the water and the development of the arc channel or the electrical

properties of the arc in even the older simple electrode configurations that had been studied. This research effort is intended to address this gap in our understanding. Current efforts of research focus on those issues which will permit the source to be used as a practical sound source in a long-range anti-submarine warfare (ASW) system. The principal anticipated advantages are that the source will be compact with a lightweight wet end. This would allow the deployment of a large array for high speed towing, which would be an important advantage over the current sources.

Approaches Taken

The characteristics of the electrical breakdown of water are being studied with the goal of understanding, to the extent possible, the fundamental processes involved. In addition, we are developing models for this process.

Experiments have been performed to establish some of the parameters involved in the process of the breakdown of water at widely varying conductivities ranging from those of tap water up to those of 50 m S/cm sodium chloride solutions.

Preliminary measurements with single and multiple gap electrodes showed that the same values of initial corona resistance are almost independent of the electrode configuration.

A model is being developed to account for the observed characteristics of the breakdown of water.

Accomplishments Completed

Arc Simulation

An investigation was initiated to study the arc portion of an electrical discharge in water via computer simulations. For most electrode configurations, the arc phase starts out with a cylindrical geometry and maintains this for most of

the arc. Because of this, our initial thrust has been completed in axially symmetric (r) one-dimensional coordinates. There are two distinct regions: (1) the exterior composed of water and (2) an interior composed of a mixture of water vapor, dissociated water vapor, and ionized hydrogen and oxygen. The boundary between the two regions moves as the arc evolves.

Since we are using cylindrical symmetry, a simple ordinary differential equation (ODE), such as the Kirkwood-Bethe model for the bubble exterior, does not apply. The evolution of the bubble exterior is accomplished with a MacCormack predictor-corrector algorithm. The full nonlinear fluid equations are used, which include equations for the evolution of the density, the velocity, and the isentropic equation of state for the pressure.

The interior of the bubble can be in any state or ratio of water, from water vapor to ionized hydrogen and doubly ionized oxygen. The interior is also now discritized, and evolution is accomplished with the nonlinear fluid equations using the Lax method. We are in the process of converting the fluid solver to the more accurate and complex MacCormack technique. The electrical component is modeled as an inductive, resistive, capacitive lumped circuit (LRC) where the resistance R is the circuit resistance along with the resistance of the bubble. The resistance of the bubble is determined by the conductivity of the plasma and the neutrals in each slice. The heat flow due to the resistance is coupled into the energy (temperature) equation. The energy equation includes changes in temperature due to variations in species concentration (through the specific heat), heat conduction by both the electrons and radiation (blackbody), energy loss by blackbody radiation, and compressional heating. Also, as mass flows into the bubble because of vaporization of the bubble boundary by blackbody radiation, the bubble boundary temperature is brought into equilibrium with the pre-existing plasma-water vapor mixture on the boundary.

The evolution of the bubble boundary is accomplished via an expanding grid. The bubble boundary is initialized to a particular grid point. The grid

expands as the bubble evolves, so the chosen boundary grid point always tracks the bubble boundary.

Preliminary results show good agreement with the current, voltage, and efficiency of energy flow into the bubble. Also, as the boundary cools due to mass influx from the blackbody radiation, a large temperature gradient (and pressure) forms. This induces large shock waves, which can be seen bouncing back and fourth, within the bubble's interior. Because the Lax solver is not effective for the resolution of shock waves, the MacCormack solver is being implemented to study these structures.

Dielectric Breakdown

About a year ago, intensive theoretical studies of ionization wave fronts in air and of the Saffman-Taylor phenomenon began. After a month of study, it was concluded that the wave front concept would involve intensive computing and would not result in a significant understanding of the dielectric breakdown. The Saffman-Taylor model showed more promising results. The instability theories developed for the oil/water interface seemed to be readily convertible to a liquid conductor, water interface. The final goal of the model was to gain a macroscopic understanding of why the leader structure branches and to predict its spatial temporal evolution.

The first step was to develop a dispersion relation for instabilities on a moving planar liquid conductor, water interface. This was accomplished easily. The next step was to develop a dispersion relation that would give the growth rate for instabilities on a moving, curved interface. Because of the difficulty and the lack of data needed to formulate this type of model, a preexisting fractal model was used to set up a database which would give us the basic branching information that our Saffman-Taylor model must produce. The intention here was to try to get some of the parameters from a semi-empirical model that could be used to place reasonable limits on the parameters needed in the more detailed model.

Unfortunately, the fractal model had one too many free parameters. It was decided to use the acoustic signal of a corona discharge as an extra piece of information to eliminate one of the free parameters. After the corona electrode was designed and built, acoustic data were taken at Lake Travis Test Station. The experiment was conducted at one depth and with three different conductivities: 0.6 m S/cm, 6 m S/cm, and 60 m S/cm. This data revealed one could not infer the details of how the electrical input to the water produced an acoustic signal.

A series of high speed photographs was taken with a Wollensak wf4 camera. The pictures show two important features. The first was that immediately after the high voltage is applied to the electrode, a dark layer appears around the anode. This feature occurs before any visible bubble is formed. The second feature is that after the dark layer disappears, a small bubble forms at the anode, and its expansion coincides with the discharge of the capacitor. A model was developed to include current conduction through the outer wall of the bubble into the bulk water. This model also included energy and particle transport mechanisms as well as the plasma resistance and effective ionization rates for a water vapor gas. Preliminary results, however, indicate that the energy-feeding process is not simple and probably depends on a branch-like structure, much like a corona in air. Basically, a small layer of steam covers the electrode and is superheated; the small vapor bubble then suddenly expands and the capacitor dumps most of its energy into it. The photographs also show that the discharge begins to occur at the base of the anode and not at the point of the anode.

Multigap electrodes

Analysis of the resistances on the multiple gap electrodes was performed to determine the inter-electrode bulk resistances. Experiments were also performed to determine the effects of the currents between electrodes. It was found from simple models that the resistance between electrodes was the same

as the resistance between two electrodes in a single gap. This meant that the current would flow around the electrodes in the multiple gaps as much as it would flow through the gaps. Thus, in salt water, a great deal of the pre-breakdown energy would be lost in the bulk salt water. A further experiment was performed to block these currents that bypassed the electrodes. The results showed significantly less current and energy consumed in the pre-breakdown phase than when the bypassing currents were not blocked. The results make a very significant difference in the energy consumed to create a given length arc in salt water. The conclusion of this work is that multiple gaps, closely spaced, will not help the formation of longer arcs in salt water. However, they do have some benefit in air and in low conductivity fresh water.

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Publications/Patents/Presentations/Honors Report

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Conference Presentations

"Assessment of a Fractal Model for Corona Discharges in Salt Water," J. C. Espinosa, H. M. Jones, A. M. Gleeson, and R. L. Rogers, 130th Meeting of the Acoustical Society of America, 28 November 1995, St. Louis, MO.

"Cylindrical Bubble Evolution and Acoustic Signature Through the Arc Phase of an Electrical Discharge," D. L. Fisher and R. L. Rogers, 131st Meeting of the Acoustical Society of America, 16 May 1996, Indianapolis, IN.

"Modifications of a Fractal Model for a Corona Discharge," J. C. Espinosa, R. L. Rogers, and A. M. Gleeson, 131st Meeting of the Acoustical Society of America, 16 May 1996, Indianapolis, IN.

Publications in Progress

There are currently two papers in progress which are expected to be submitted to the *Journal of the Acoustical Society of America*:

- "Interactions and Acoustic Characterization of Multiple Spark-Generated Bubbles," Jeffrey A. Cook, Austin M. Gleeson, and Robert L. Rogers.

- "Breakdown Characteristics of Water for Low to Moderate Conductivity Salt Solutions," R. L. Rogers, J. C. Espinosa, and H. M. Jones.

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Papers accepted by the Journal of the Acoustical Society of America

- "A Spark-Generated Bubble Model with Semi-Empirical Mass Transport," Jeffrey A. Cook, Austin M. Gleeson, Randy M. Roberts, and Robert L. Rogers (currently under revision).

- "Energy Partition of Underwater Sparks," Randy M. Roberts, Jeffrey A. Cook, Austin M. Gleeson, Thomas Griffy, and Robert L. Rogers (final revision accepted and still awaiting publication).

Key Personnel

(1)   James C. Espinosa (Ph.D. student in physics)
(2)   Dr. Austin M. Gleeson (Research Faculty)
(3)   Dr. Hugh M. Jones (Post-Doctoral Fellow)
(4)   Dr. David L. Fisher (Post-Doctoral Fellow)
(5)   Dr. Robert L. Rogers (Principal Investigator)